Frequency-Reconfigurable E-Plane Filters Using MEMS Switches

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Abstract. In this paper a new concept for the design of reconfigurable bandpass filters showing very high unloaded Q-factor is presented. The new solution uses rectangular waveguide resonators loaded with a reconfigurable E-plane circuit. Ohmic MEMS switches are placed around E-plane metal strips so as to modify the TE_{101} mode resonant frequency, thus changing the central frequency of the filters. Unloaded Q-factors over 1000 and tuning ranges up to 10% can be achieved. Preliminary measurements of a 3rd order bandpass hardwired filter at 10 GHz show 625 MHz frequency shift (6.25%) with unloaded Q-factors above 1000. The final version of the filter using actual RF MEMS is presently under fabrication at FBK.

1. Introduction

Tunable and reconfigurable bandpass filters will be key elements in future telecommunication systems both for satellite and terrestrial applications. Size and weight of tunable and multi-standard satellite front-ends will be reduced and innovative programmable and reconfigurable RF-systems will be developed and realised, if efficient and reliable solutions for electronically tunable filters are found. High unloaded Q-factor (>500), wide tuning range (5-10%) and low manufacturing cost should be provided.

Magnetically tunable filters show high Q-factors but they are bulky and consume a considerable amount of DC power [1]. Planar tunable filters using MEMS or varactors allow for an easy implementation but provide low Q-factors (<300) [2]. Evanescent-mode cavities [3], dielectric-loaded resonators [4] and ridged waveguide resonators [5] achieve higher unloaded Q-factors (>500) but they require complex MEMS arrangement.

The use of ohmic cantilever RF-MEMS switches for the realisation of very high-Q (up to 1000) bandpass reconfigurable filters has been proposed by the authors of the present paper in [6] and [7], where an accurate review of the reconfigurable and tunable filter state of the art is also described. A similar concept yielding very high Q-factors has been implemented in E-plane bandpass filters with a reconfigurable bandwidth [8].

Magnetically tunable E-plane filters [9] and tunable E-plane filters using both varactors and capacitive MEMS [10][11] have been developed in last decades yielding significant central frequency tunings with Q-factors up to 500. A new concept of reconfigurable bandpass filters leading to very high Q-factors (>1000) is proposed in this paper. The filter is based on rectangular waveguide resonator loaded with an E-plane metal strip on a low-loss substrate [12]. Ohmic RF MEMS switches are used to modify the length of the metal strip so as to change the resonant frequency of the dominant the TE101 mode thus the filter passband frequency.

To illustrate and validate the proposed tuning principle, a 3rd order bandpass filter at 10 GHz has been designed and fabricated using equivalent hardwired connections emulating the MEMS states.

2. New Tuning Principle

The resonator depicted in Fig. 1 consists of a waveguide section comprised by two E-plane septa of length *d*. The latter determines the input/output (inductive) coupling, while the distance *l* between the septa determines the resonant frequency of the TE_{101} mode. An additional E-plane conductive strip between the septa is used to lower the resonant frequency of the TE_{101} mode. Thin longitudinal lines, each being interrupted in the middle by a MEMS switch, connect both ends of the central strip to the coupling septa. In the following the structure in Fig. 1 is called strip-loaded E-plane resonator.

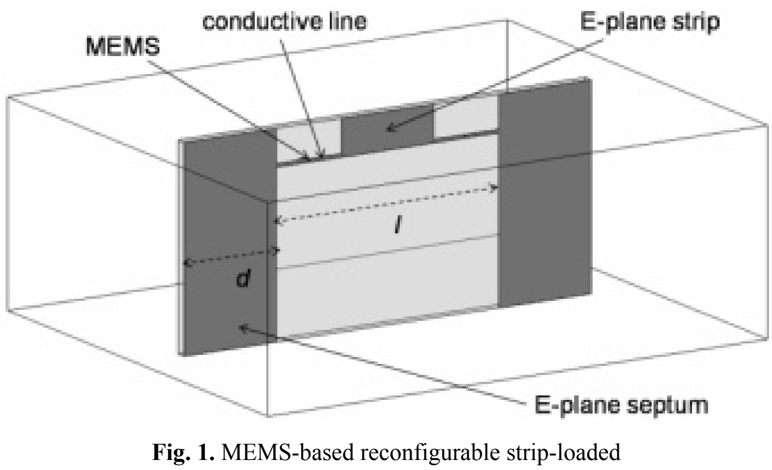

Fig. 1. MEMS-based reconfigurable strip-loaded E-plane resonator.

The MEMS switches can be realised as ohmic cantilever switches. As is well known, in the on-state the switch is closed and can be modelled as a very low series resistance (R_{on}), while in the off-state the switch is open and can be modelled as a low series capacitance (C_{off}) [13].

The tuning principle of the strip-loaded E-plane resonator is as follows. When both MEMS are closed, the electric field in the longitudinal plane is confined below the conducting lines, while when the MEMS are open, the electric field goes through the conducting lines. As a result, the resonant frequency is lowered by switching the MEMS off. The amount of the frequency shift can be controlled by suitably choosing the geometry of the E-plane printed circuit.

3. Reconfigurable Resonator Design

As an example, the practical design of a MEMS-reconfigurable resonator operating in the X band (centre frequency is 10 GHz) is illustrated in this section. The full-wave HFSS ® model is shown in Fig. 2a.

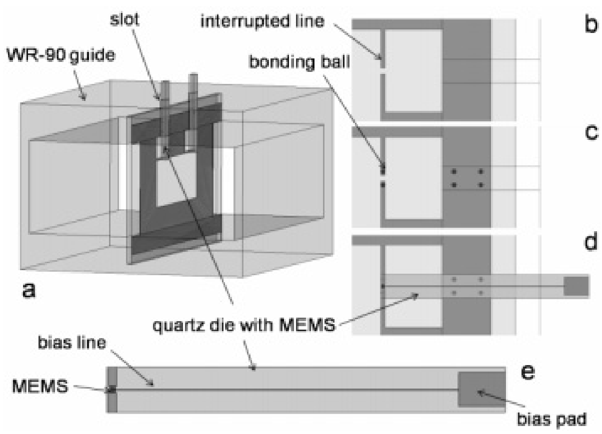

Fig. 2. MEMS-reconfigurable strip-loaded E-plane resonator (a), flip-chip mounting of the MEMS quartz die (b) (c) (d), MEMS quartz die (e).

The E-plane circuit pattern is realised on a 500µm thick quartz substrate (ε_r = 3.78; tanδ = $1{\cdot}10^{-4}$). The longitudinal lines are 200µm width (Fig. 2b). The cantilever MEMS are realised on 500µm thick quartz dies and mounted at the centres of the longitudinal lines using flip-chip technology (Fig. 2c and 2d). Small gold bonding balls (typically 200µm diameter) are employed both to solder the MEMS interfaces to the lines and to support the quartz dies on the substrate. Quartz is preferred to silicon because of its lower εr and tanδ. As shown in Fig. 2a, the thin quartz dies protrude beyond the waveguide broad wall in order to allow the connection of the MEMS bias lines (Fig. 2e). The slots opened in the waveguide broad wall are thin enough not to interrupt the flowing currents, thus preventing or minimising undesired radiation.

Series ohmic cantilever MEMS switches have been considered. They consists of 110 µm wide and 170 µm long gold beams suspended above an interrupted microstrip line. Similar designs previously manufactured by FBK, Trento Italy, showed an on-state resistance R_{on}=0.9 Ω and an off-state capacitance C_{off} =10 fF. The 10 µm wide bias lines are realised in high resistivity polysilicon [2], [13].

The structure has been carefully modelled by HFSS ® including the bias lines, the lossy substrates, the actual material conductivity as well as any undesired radiation through the thin slots. Fig. 3 shows the simulated scattering parameter $|s_{21}|$ for both MEMS states.

As can be seen, the off-state response is down shifted by 650MHz (6.5%) with respect to the on-state. The input/output coupling (K_{s1}) in the on-state is 0.1, whereas it is 10% lower in the off-state. The total unloaded Q-factor is 1430 and 1590 for the on- and off-state respectively.

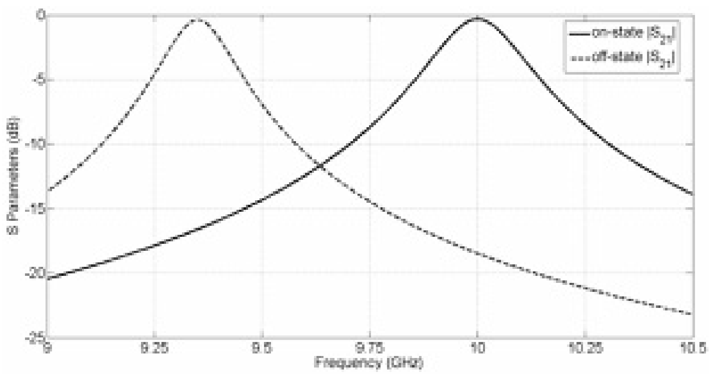

Fig. 3. Simulated $|s_{21}|$ (Ansoft HFSS) of the X-band reconfigurable strip-loaded E-plane resonator of Fig. 4: on-state MEMS (solid blue line); off-state MEMS (dashed red line).

According to HFSS ® simulations, frequency shifts up to 10% are obtained maintaining the unloaded Q-factors above 1000 for both MEMS states.

4. Preliminary Measurements and Future Work

In order to validate the proposed approach, a 10 GHz 3^{rd} order filter has been designed manufactured and tested. Photographs of the disassembled structure are shown in Fig. 4.

The ohmic MEMS switches have been replaced by hardwired connections, *i.e.* open- or short-circuits, which emulate the two MEMS states: a 100 µm thick continuous copper line is used for the on-state MEMS, whereas a 100 µm gap in the lines is used for the off-state MEMS.

The two hardwired configurations (on- and off-state) are alternatively assembled in the waveguide (Fig. 4). The substrate is Arlon DiClad 880 (ε_r = 2.17; tanδ = $1 \cdot 10^{-3}$).

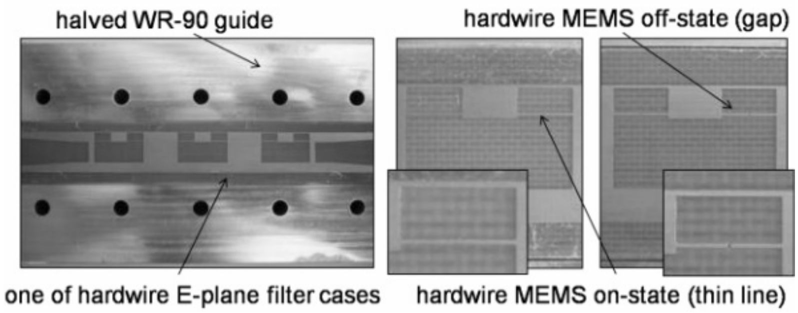

Fig. 4. Photographs of the 10 GHz.3rd order reconfigurable bandpass filter employing hardwired connections.

The simulated and measured insertion loss and return loss of the band-pass filter in the two configurations are shown in Fig. 5 and 6 respectively.

A frequency shift of 625 MHz (6.25%) has been measured; this value fits well with the 650 MHz simulated frequency shift. The measured insertion losses at centre frequency are 0.30 dB and 0.31 dB for the on- and off-state respectively (Fig. 5). The measured 25 dB equiripple relative bandwidths are 3% and 2.8% (Fig. 6), corresponding to measured unloaded Q-factors of 1050 and 1100 respectively.

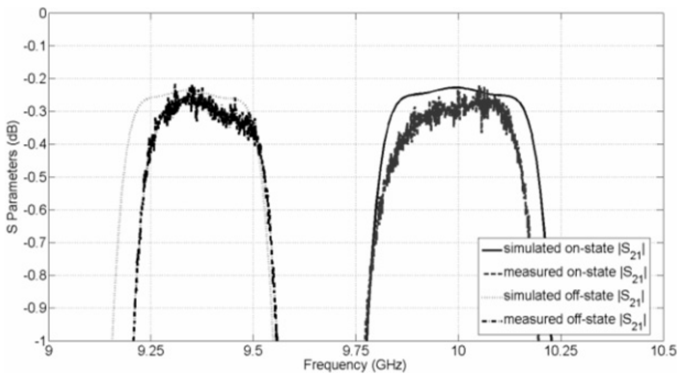

Fig. 5. Simulated and measured $|s_{21}|$ of the 3rd order hardwired filter prototype on-state MEMS (simulated $|s_{21}|$ solid blue line, measured $|s_{21}|$ dashed red line); off-state MEMS (simulated $|s_{21}|$ dotted green line, measured |s21| dot-dashed black line).

The simulated unloaded Q-factor is 1400 and 1450 for the on- and off-states respectively, so the corresponding measured values are roughly 25% lower for both states. This is to be ascribed to a loose contact between the printed circuit and the waveguide wall.

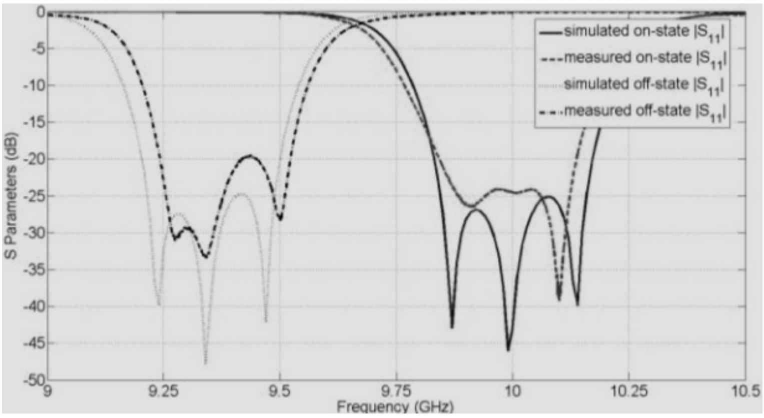

Fig. 6. Simulated and measured $|s_{11}|$ of the 3rd order hardwired filter prototype: on-state MEMS (simulated $|s_{11}|$ solid blue line, measured $|s_{11}|$ dashed red line); off-state MEMS (simulated $|s_{11}|$ dotted green line, measured |s11| dot-dashed black line).

A 6.5% shrink of the relative bandwidth in the off-state is observed compared to the on-state, because of small variations of the filter couplings. The measurements are very promising both in terms of unloaded Q-factor and bandwidth robustness especially when compared to other tunable filter realizations presented in the literature [5][6].

A 3rd order E-plane reconfigurable filter at 10 GHz employing real ohmic cantilever MEMS switches is being manufactured by FBK (Fondazione Bruno Kessler) using an established eight-mask surface micro-machining process on 500µm thick quartz substrate [2][13].

5. Conclusion

A new concept has been proposed for high-Q MEMS-based reconfigurable bandpass filters. A waveguide resonator is employed consisting of a rectangular waveguide section comprised between two metallic E-plane septa and loaded with an E-plane conductive strip.

The strip is connected to both septa by conducting lines that can be switched on and off by RF-MEMS. Therefore, the TE_{101} mode resonant frequency can be changed depending on the MEMS state. The proposed tuning principle provides a frequency tuning up to 10% and unloaded Q-factors above 1000.

The tuning concept has been validated by fabricating and measuring a 10 GHz 3rd order bandpass filter where MEMS switches have been replaced by hardwired connections. A 6.25% frequency shift and unloaded Q-factors above 1050 have been measured in agreement with the HFSS simulations. Return loss variation due to the tuning is negligible, while a little relative bandwidth change occurs (6.5%).

The final version of the filter using actual RF MEMS is presently under fabrication at FBK.

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